

COFS II
3-D DYNAMICS AND CONTROLS TECHNOLOGY

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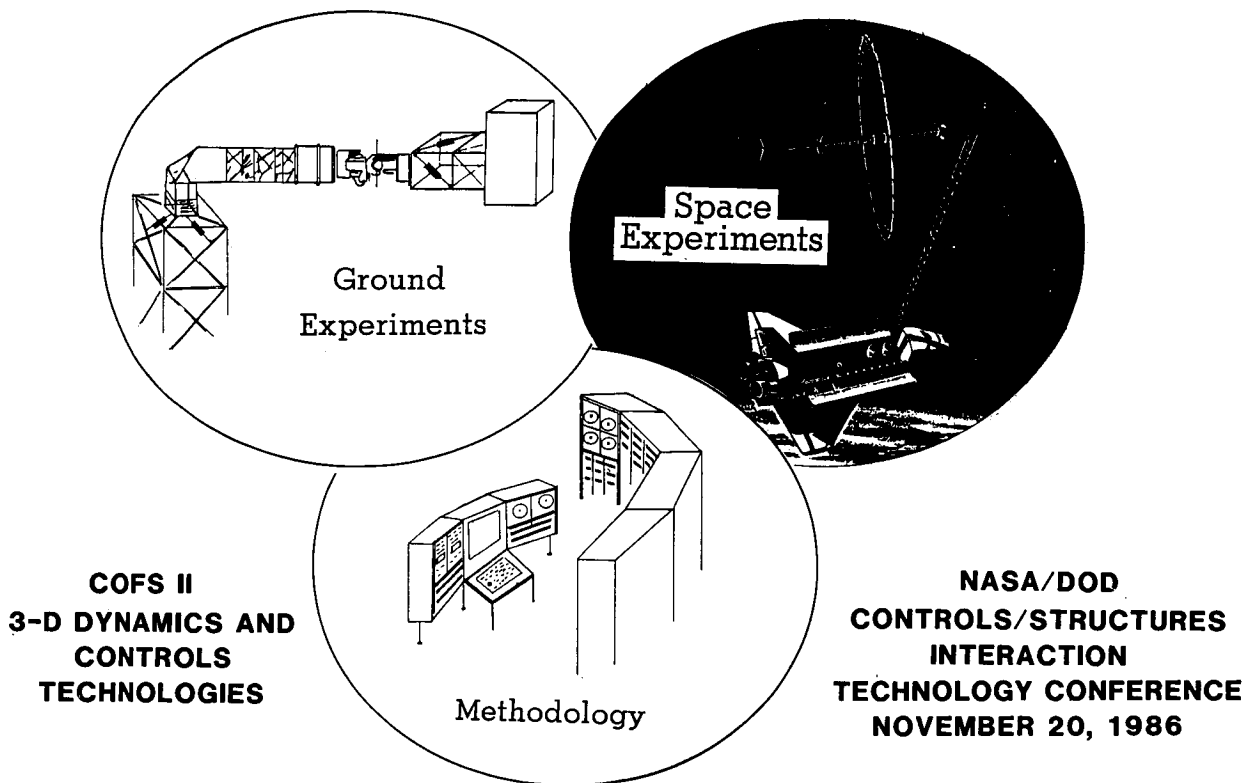
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INTRODUCTION

NASA has initiated a program to focus the development of Controls/Structures Interaction (CSI) technologies for the next generation of large, flexible spacecraft. This program, called "Control Of Flexible Structures (COFS)", will address critical technologies in the areas of structural dynamics and controls through comprehensive ground and flight testing of the fundamental elements of large, flexible space structures. The COFS program is a series of projects with the objective of developing a validated CSI technology data base for the suppression of inherent dynamic responses and avoidance of the undesirable interaction between flexible structures and controls in these spacecraft. The following paper discusses the current development plans for the second in this series of projects, COFS II, Three-Dimensional Dynamics and Controls.

COFS II CONTROL OF FLEXIBLE STRUCTURES



PROJECT OBJECTIVES

COFS II is the natural extension of the beam dynamics and controls experiments undertaken in the initial project of the COFS program and will advance the technology data base into the areas of three-dimensional, multibody configurations. The COFS II project will build on the ground and flight technologies developed in COFS I and will improve on the development of a multi-input/output control system for the suppression of undesired disturbances in these large, flexible spacecraft. Specifically, COFS II will evaluate prediction techniques used to define the dynamic and control characteristics of space structures through a comparison of theoretical, ground test and on-orbit test data. The project will develop advanced control techniques and on-orbit validation procedures which will lead to optimized spacecraft performance in minimal on-orbit test time. The COFS II project involves the space structures and controls community from universities, industry and government through a formal Guest Investigator Program in which researchers are selected to participate in all program activity phases.

- **DEVELOP AND EVALUATE THE METHODOLOGIES INVOLVED
IN MODELING AND CONTROLLING LARGE, FLEXIBLE,
3-D STRUCTURES IN SPACE**

COFS WORKSHOP RESULTS

A Controls/Structures Interaction (CSI) workshop was held at NASA Langley Research Center on August 27-28, 1985. The purpose of the workshop was to review the proposed COFS I, Beam Dynamics and Controls project, the COFS II, Three-Dimensional Dynamics and Control project and the methods of interacting the CSI community in the experimental phases of each of these projects.

Members of the CSI community made up of individuals from major universities, related industries and government research organizations were asked to define major technology deficiencies for the next generation of large space structures. Nine critical technology needs were identified which concentrated on the control of the dynamic interaction between the parts of a multibody space structure.

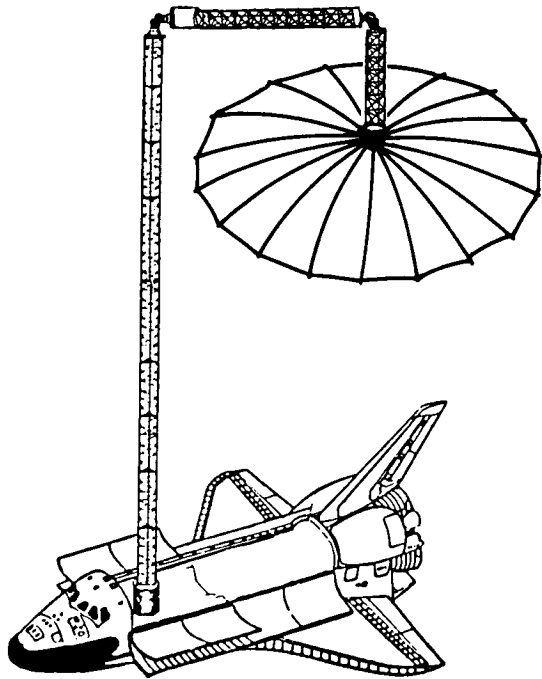
The workshop attendees were also asked to identify viable flight configurations which would provide the basis for critical technology development. Most panels agreed that the configuration which included multibody beams attached by gimbals to a "realistic antenna" would provide the capability for developing the major portion of the critical technologies.

- **DEFINED CRITICAL CONTROLS AND STRUCTURES
TECHNOLOGY REQUIREMENTS FOR 3-D SPACE
EXPERIMENTS**
- **IDENTIFIED 3-D CONFIGURATION FOR GROUND AND
ON-ORBIT TESTING**

WORKSHOP CONFIGURATION/TECHNOLOGIES

The recommended workshop configuration shown in the figure was generated utilizing the COFS I Mast beam, a deployable boom attached to the tip of the Mast by means of a gimbal, and a real antenna attached to the boom by means of a gimbal. The boom modal characteristics should be capable of combining with the structural modes of the Mast to provide interactive modal characteristics of research interest. The antenna should have a mesh surface with the capability of changing the surface shape to improve the antenna performance.

The critical technology needs for the three-dimensional configuration are primarily related to the stabilization of the multibody structure and control of that structure during repositioning. The primary dynamic characterization of the flight system will provide the basis for developing control methodologies to stabilize the structure, minimize the dynamic disturbances caused by deployment, maneuvering and articulation of the secondary boom or antenna, and pointing the antenna at a prescribed location. The successful development and validation of these primary technologies will permit further development of adaptive control techniques for more complex configurations.

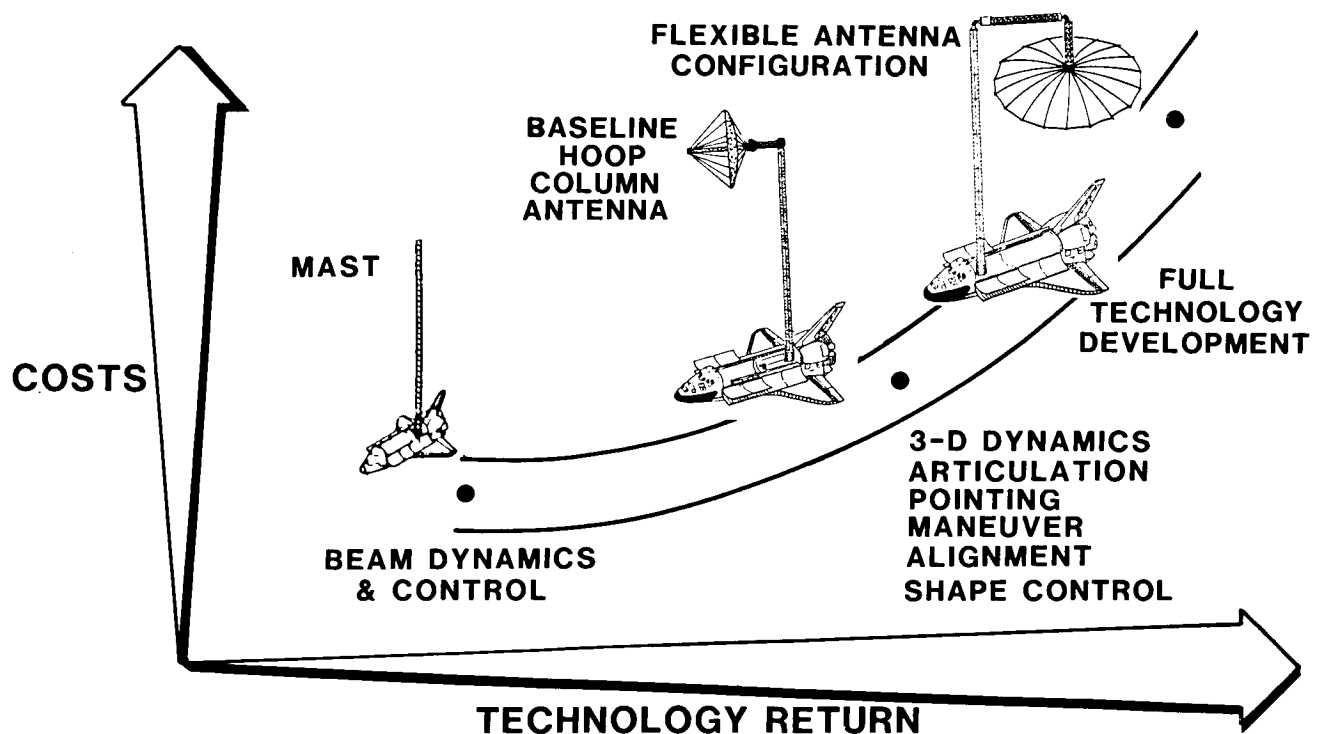


CRITICAL TECHNOLOGY NEEDS

- POINTING/AIMING
- ARTICULATION
- SLEWING
- SHAPE CONTROL
- MANEUVER LOAD
- ALIGNMENT
- SYSTEMS IDENTIFICATION
- STRUCTURAL EVALUATION
- DEPLOYMENT CHARACTERIZATION
- VIBRATION CONTROL
- ADAPTIVE CONTROL

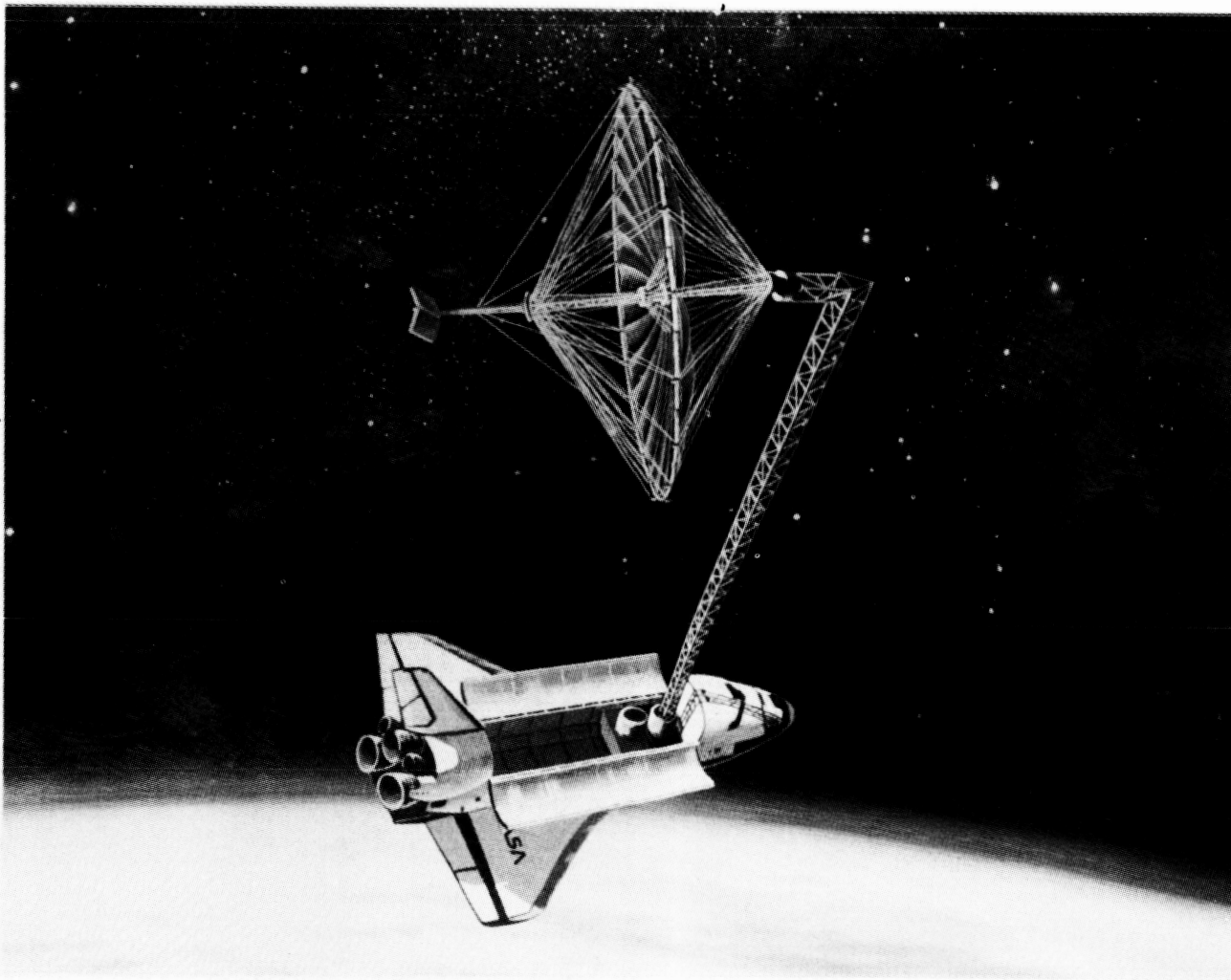
COFS II CONFIGURATION COST OPTIONS

Estimates of the COFS II project costs were completed for various types of large, flexible, three-dimensional configurations which would satisfy the critical technology recommendation of the workshop. The results of this exercise are shown on the figure with increasing project costs as the vertical axis and increasing technology return as the horizontal axis. The COFS I project, Beam Dynamics and Control, was shown as a bench mark of the relative project development costs. Obviously, as the number of technologies and the complexity of the configuration increases, the project costs also increase. The workshop configuration provides the full development and validation of the primary technologies; however, the very high design, fabrication and development test costs for this concept preclude its utilization as the government proposed configuration. However, most of the technologies can be developed and validated through the testing of a simplified version of the workshop configuration pictured in the figure.



COFS II BASELINE CONFIGURATION

The simplified version of the workshop configuration shown in the previous figure is presented here as an artist's rendition. This concept includes the NASA Langley Research Center designed and developed hoop-column antenna attached to the tip of the COFS I Mast by means of a two-degree-of-freedom gimbal assembly. This concept was utilized as the study configuration for an in-house engineering analysis to determine the feasibility of attaching a realistic antenna to the Mast and to estimate the relative cost of accomplishing the desired technology development program. The antenna will be stowed in a separate canister in the shuttle bay and will be removed by the Mast during its deployment. The antenna will be deployed on command when the Mast reaches adequate height to eliminate interference with the shuttle doors and characterization of the flight system dynamics will be initiated. On-orbit validation of previously developed control algorithms will commence and will continue at various deflections of the antenna and at various beam heights. Upon completion of the flight tests, the antenna and Mast will be restowed into their respective canisters for the landing phase of the mission. Upgrading of the predicted COFS II structural characteristics based on the on-orbit test data will provide the confidence for developing and validating adaptive control techniques to be tested on the second flight of this configuration.



HYBRID TEST APPROACH

A major contribution of the COFS II project will be the development and validation of a hybrid test technique for the ground testing of very large, flexible, 3-D space structures. The structural characterization of the flight system will be accomplished by combining the smaller hardware components such as the baseline adapter and two-degree-of-freedom gimbal with analytical simulations of the Mast and hoop-column antenna. This hybrid system will simulate the actual flight system and provide the capability to validate experimental control algorithms, verify new control synthesis techniques, and to develop adaptive control concepts. The establishment of this testing technique through the COFS II project will be highly instrumental in the ground validation and on-orbit success of future spacecraft missions.

DEFINITION: **HYBRID SYSTEM - COMBINATION OF REAL HARDWARE AND
COMPUTER SIMULATION OF LARGE COMPONENTS AND/OR
SUBASSEMBLIES**

APPROACH:

- **ACCOMPLISH LARGE COMPONENT & SUBASSEMBLY GROUND TESTS**
- **DEVELOP COMPUTER SIMULATION OF COMPONENTS AND/OR
SUBASSEMBLIES**
- **COMBINE SMALL COMPONENT HARDWARE WITH COMPUTER
SIMULATIONS OF LARGE HARDWARE TO CREATE FLIGHT
SYSTEM SIMULATOR**
- **UTILIZE FLIGHT SYSTEM SIMULATOR TO VERIFY CONTROL ALGORITHMS**

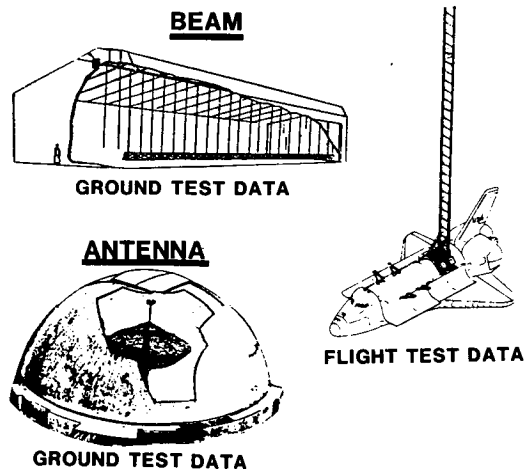
TEST OBJECTIVES:

- **DETERMINE DYNAMIC AND CONTROL CHARACTERISTICS OF
COUPLED SYSTEM AND COMPARE TO FLT SYS PREDICTIONS**
- **VERIFY GI CONTROL ALGORITHMS ON FLIGHT SYSTEM**
- **VALIDATE HYBRID TEST APPROACH FOR LARGE SPACE STRUCTURES**

COFS II HYBRID TEST METHOD

The development method for the COFS II hybrid test technique is depicted in the following figure. The structural characteristics of the very large pieces of the COFS II flight system will be obtained from a combination of individual ground and/or on-orbit testing of these structures. Analytical simulations of these structures will be generated utilizing knowledge generated from basic Research and Technology development within the CSI community and in-house Langley expertise. These simulations of the large structures will be combined with the smaller articulation hardware to provide a combination of hardware and software which simulates the dynamic characteristics of the flight system in the on-orbit environment. The resultant high fidelity simulation should then provide the capability of verifying and validating developed control methodologies prior to actual flight validation.

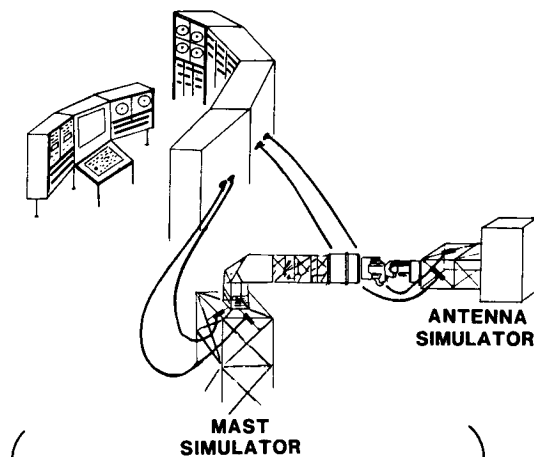
COMPONENT AND SUBASSEMBLY TESTING



BASIC R&T EXPERIENCE

- CONTROL CONCEPTS
- MODELING
- SYSTEM ID

HYBRID TEST SIMULATOR



HI-FI SYSTEM SIMULATION

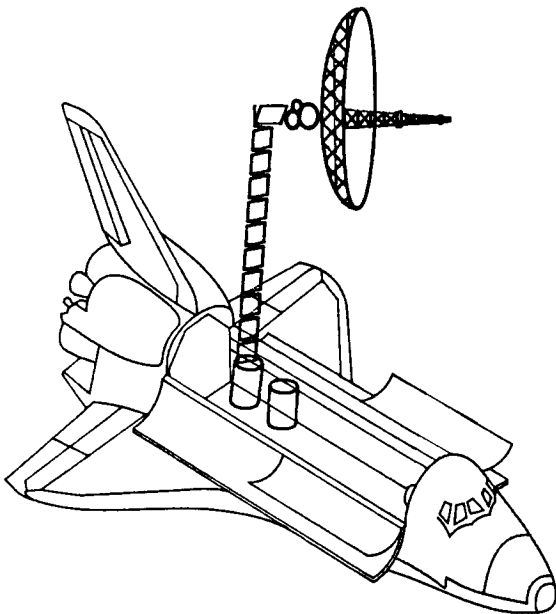
FLIGHT EXPERIMENT OBJECTIVES

The baseline COFS II configuration will provide the opportunity of developing a better understanding of the control/structural interaction characteristics of a multibody spacecraft in a zero-g environment. Techniques for evaluating deployment, structural dynamics, systems identification and possible procedures for fault detection, isolation and reorganization of sensor faults (FDIR) will be examined on the flight system during flight. Upon achieving a stable platform through alignment and vibration control, the gimbal will be used to articulate the antenna and examine pointing, slewing and articulation control algorithms previously developed and verified on the ground. Quasi-static shape control of one quadrant of the antenna will be demonstrated along with control at the hoop. Maneuver load control utilizing inputs from the shuttle will be developed and adaptive control techniques for the complex system will be evaluated. In addition, the flight results will be used to establish the viability of the hybrid testing techniques used in predicting on-orbit performance of a large, flexible, and complex structure.

- **DEVELOP AND VALIDATE ADVANCED CONTROL METHODOLOGIES ON A LARGE, 3-D FLEXIBLE STRUCTURE IN A ZERO-G ENVIRONMENT**
- **IDENTIFY AND CHARACTERIZE THE DYNAMICS OF A LARGE, 3-D FLEXIBLE STRUCTURE IN A ZERO-G ENVIRONMENT**
- **CORRELATE FLIGHT TEST RESULTS WITH GROUND TEST AND ANALYTICAL PREDICTION**
- **ESTABLISH VIABILITY OF HYBRID TESTING TECHNIQUES FOR PREDICTING ON-ORBIT PERFORMANCE OF LARGE, FLEXIBLE, AND COMPLEX SYSTEMS**

STRUCTURAL EVALUATION & SYSTEMS IDENTIFICATION

The individual technology development and validation approaches will be shown in the next series of figures. During the initial deployment of the flight experiment, its dynamic characteristics will be evaluated and compared to the predicted system characteristics generated from analytical models and the hybrid test system. This characterization will provide the validation of the predicted flight system dynamics and interaction and verify that the control algorithms developed on the ground will provide the damping and stabilization required for the flight experiments.



OBJECTIVES:

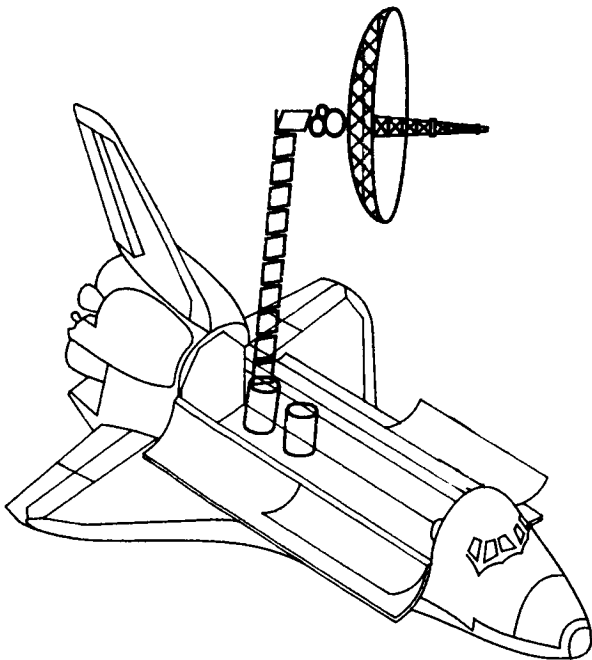
- CHARACTERIZE FLIGHT SYSTEM
- EVALUATE PREDICTION TECHNIQUES

APPROACH:

- DEPLOY BEAM & ANTENNA
- DETERMINE FLIGHT SYSTEM
DYNAMIC CHARACTERISTICS
- COMPARE WITH GROUND RESULTS
& ANALYTICAL PREDICTIONS

ARTICULATION & POINTING TECHNOLOGIES

Two of the key control technologies requiring development and validation for the next generation large space structure are controlled articulation and highly accurate pointing of the antenna-like structure. Various techniques will be developed by the Guest Investigators which will stabilize the beam structure, articulate the antenna by the two-degree-of-freedom gimbal and point it in a prescribed location. The control algorithms generated for this purpose will be verified with the hybrid simulator and then validated on the flight system in orbit on the shuttle. The flight results will then be utilized to upgrade the control techniques to provide a more efficient method of articulation and pointing of the antenna surface.



OBJECTIVES:

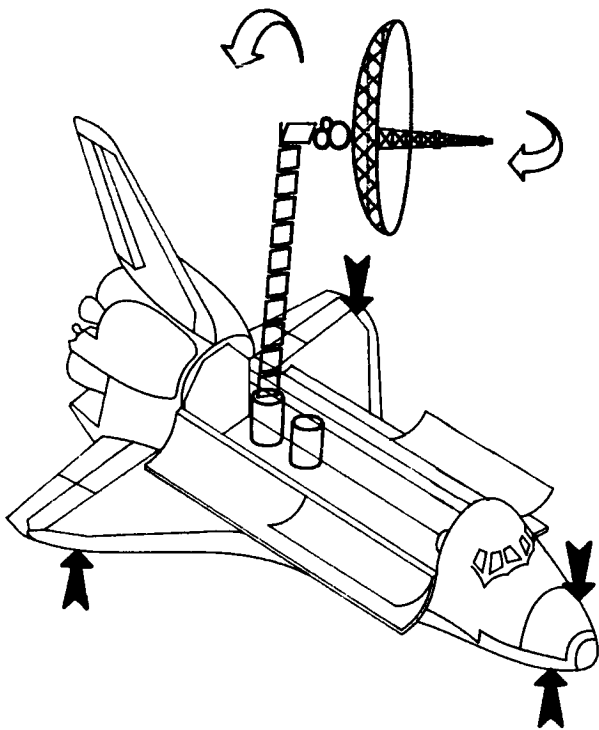
- DEVELOP ANTENNA ARTICULATION TECHNIQUES
- DEMONSTRATE STABLE POINTING WITH ANTENNA

APPROACH:

- SLEW ANTENNA WITH 2 DOF GIMBAL
- USE CONTROL ALGORITHMS TO STABILIZE FLIGHT STRUCTURE
- EVALUATE ANTENNA STABILITY & POINTING

SLEWING & MANEUVER LOAD CONTROL TECHNOLOGIES

When the COFS II flight system is fully deployed, it will extend between 30 and 60 meters from the shuttle bay with the tip of the antenna offset from the beam up to 20 meters. The beam, antenna and gimbal are subjected to a significant maneuver load during a sustained vernier reaction control system firing. The articulation of the antenna by the gimbal will also induce a slewing motion into the column support of the antenna and a torsional loading on the beam. Control techniques to alleviate these loads, dampen the disturbances caused by maneuver or slewing, and stabilize the flight system will be developed, verified through the ground hybrid simulator and validated on the baseline flight system during the on-orbit experimentation. These control methods will be further upgraded based on the on-orbit test results.



OBJECTIVES:

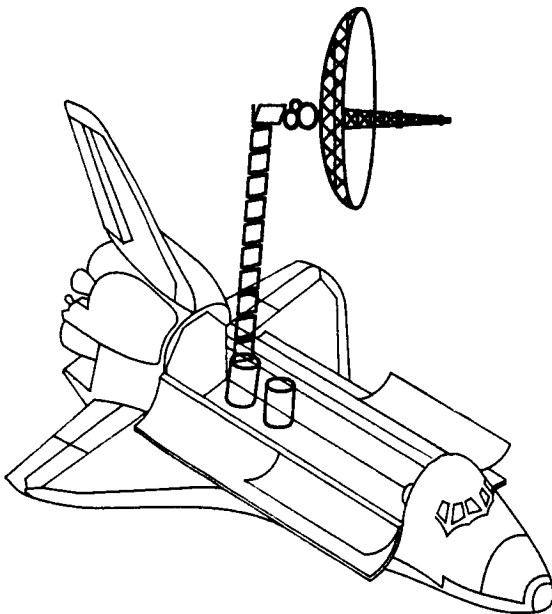
- ALLEVIATE SHUTTLE MANEUVER LOADS
- MINIMIZE DYNAMIC DISTURBANCES
FROM INDUCED MOTION

APPROACH:

- CHANGE SHUTTLE ATTITUDE OR
SLEW ANTENNA
- EVALUATE FLIGHT SYSTEM DYNAMICS
- USE CONTROL TECHNIQUES TO
MINIMIZE DISTURBANCES

SHAPE CONTROL & ALIGNMENT TECHNOLOGIES

A means of determining the precise shape of the antenna surface mesh is required in order to improve the efficiency of very large, flexible antennas in space. The COFS II baseline configuration will provide the mechanism for controlling the surface shape of one quadrant of the antenna and the antenna hoop through individual actuators and sensors attached to the lanyards (hoop/surface mesh chords). Precise location of the surface mesh, the hoop and the beam structure that the antenna is attached to, will be attained through optical/digital sensors. Quasi-static control methodologies will be developed, verified and validated during the on-orbit testing of the baseline flight system. It is hoped to achieve total reshaping of one quadrant of the antenna within five minutes and to within 0.2 millimeters of a predetermined shape.



OBJECTIVES:

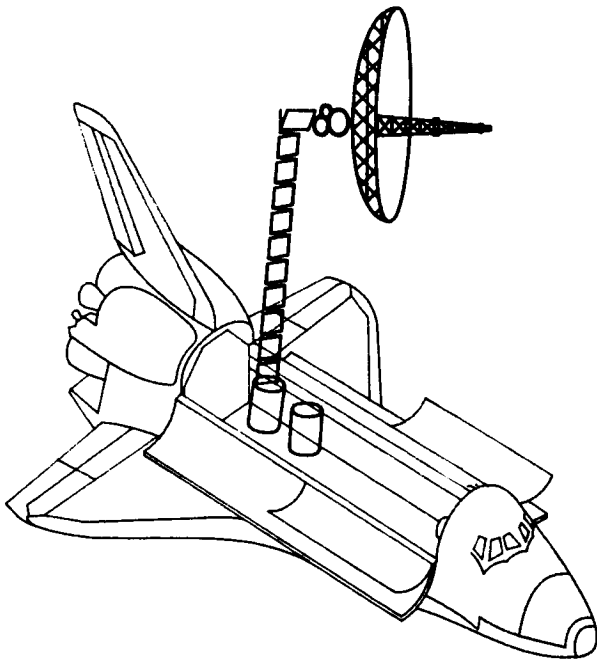
- DEVELOP PRECISE BEAM ALIGNMENT & CONTROL TECHNIQUES
- IMPROVE ANTENNA EFFICIENCY THROUGH CONTROL OF SURFACE MESH

APPROACH:

- STABILIZE BEAM AND ANTENNA STRUCTURE
- ALIGN HOOP & ANTENNA CENTER COLUMN
- DETERMINE SURFACE MESH LOCATION
- ADJUST MESH TO OPTIMIZE SHAPE

FAULT DETECTION, ISOLATION AND REORGANIZATION TECHNOLOGY

In order to account for sensor/actuator malfunctions during long periods of space utilization of these very large structures, methods must be developed to reorganize the sensors and actuators such that alternate control techniques can be applied to manipulate or stabilize the structures. The COFS II baseline sensors and actuators will have the capability of being utilized in various groupings in order to understand and develop the techniques required to verify the FDIR technology. Simulated malfunctions of sensors/alternators will be achieved by ignoring signals from selected sensors or actuator and reorganizing the information to perform a specific control function during the flight test experimentation.



OBJECTIVES:

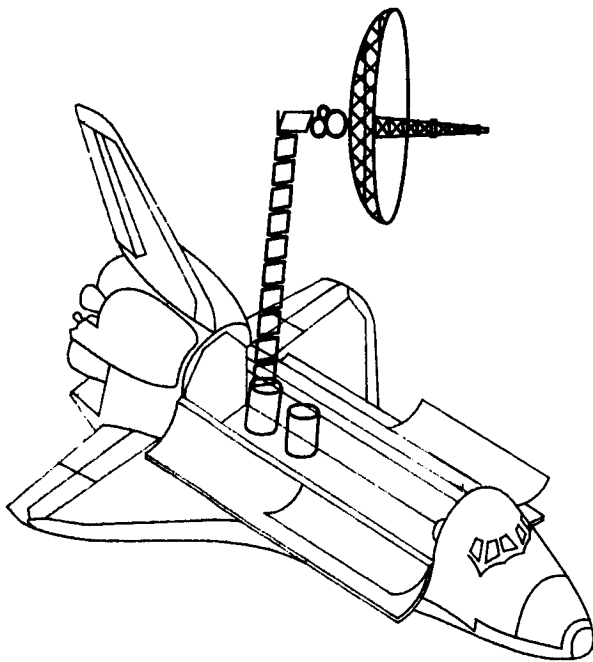
- DEVELOP FAULT DETECTION TECHNIQUES
- EVALUATE ISOLATION ALGORITHMS
- VALIDATE REORGANIZATION METHODS

APPROACH:

- SIMULATE AN EXPERIMENT SENSOR FAULT
- TEST SYSTEM TO ISOLATE FAULTY SENSOR
- DETERMINE ALTERNATE APPROACH TO MEASURE SYSTEM DYNAMICS
- REORGANIZE SENSOR INPUTS TO CONTINUE FLIGHT EXPERIMENT

ADAPTIVE CONTROL TECHNOLOGY

The goal of the controls community is to develop techniques which automatically compensate for all variations in the predicted characteristics of a large space structure, analyze the characteristics of dynamic inputs to the structure and eliminate vibrations, low frequency dynamics and any other destabilization factors. The COFS II baseline configuration will be utilized to evaluate preliminary concepts for adaptive controls which may lead to the anticipated goal. Control algorithms developed by the Guest Investigators will be verified on the hybrid simulator and validated on-orbit after previously discussed technologies have been fully developed and validated.



OBJECTIVES:

- ESTABLISH A CONTROL METHOD TO ACCOMMODATE VARIATIONS IN SYSTEM DYNAMICS AND UNCERTAINTIES IN SYSTEM PERFORMANCE

APPROACH:

- DEVELOP SYSTEM ANALYTICAL MODELS
- PREDICT SYSTEM PERFORMANCE
- DEVELOP CONTROL METHODS FOR REDUCING SYSTEM PERFORMANCE DEGRADATION
- VALIDATE ADAPTIVE CONTROL ALGORITHMS DURING FLIGHT

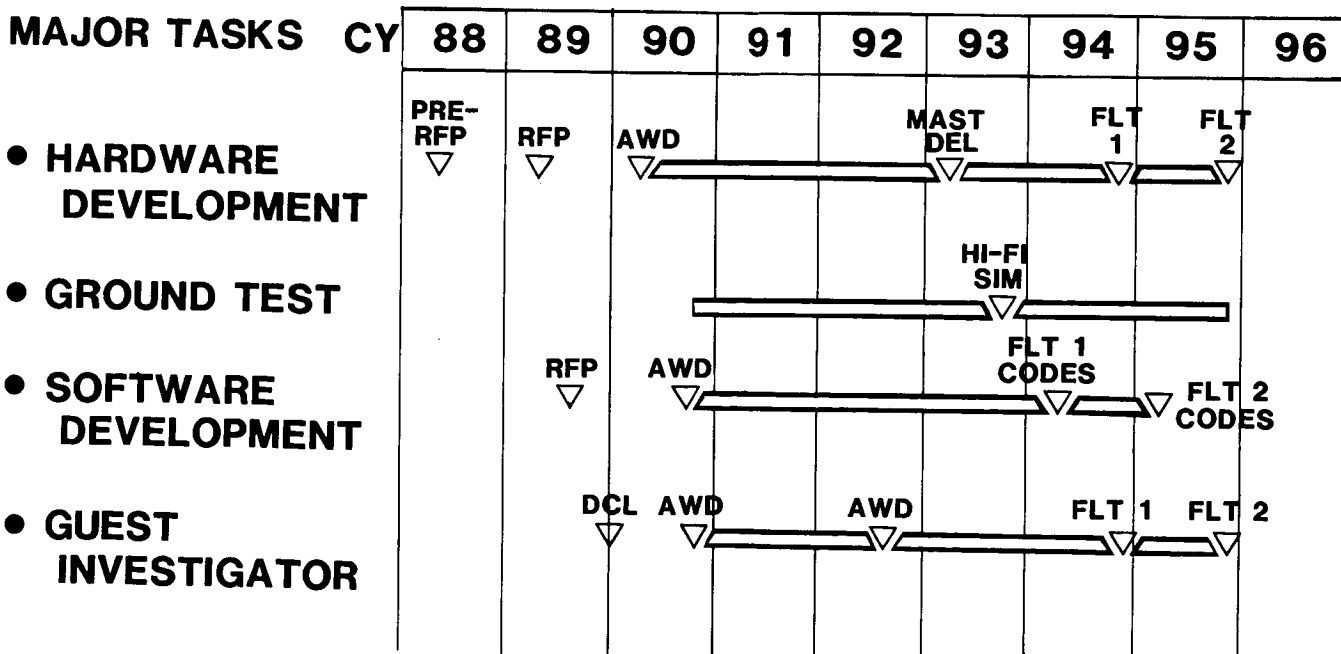
COFS II PROJECT SCHEDULE

The COFS II flight hardware development contract will be awarded early in 1989. This contract will include the design, fabrication, and testing of the flight hardware to be mounted in the shuttle bay for on-orbit testing and the prototype hardware required to construct the hybrid test system. A preliminary Request For Proposal (RFP) which identifies the primary technology goals, system specifications and specific project objectives will be released approximately 12 months prior to the official RFP. This will allow contractors adequate time to evaluate alternate hardware concepts which might provide equivalent or better technology return to the CSI community for the government investment. The current flight dates for the COFS II experiments are expected to occur in late 1993 and 1994.

The development of the hybrid simulator of the COFS II flight system will begin shortly after the award of the hardware development contract. Some of the large component and subassembly tests will be conducted within the Base R & T programs and the COFS I project prior to the initiation of the ground test task. The simulator will be constructed at NASA Langley and will be available to the hardware and software contractors and the Guest Investigators.

The software development contract will be awarded shortly after the hardware development contract and will provide the operational, baseline applications and Guest Investigator software development, the simulations of the large component dynamics to be used in the hybrid test system, and all required flight coding.

The Guest Investigator (GI) contracts will be initiated through the same procedures discussed for the COFS I project and will begin shortly after the award of the hardware development contract. Separate GI contracts will be awarded for each of the COFS II flights.



COFS II PROCUREMENT STRATEGY

The prime hardware system contractor will have the responsibility for delivering a totally integrated, operational, and flight safe system to the shuttle payload integration facility at KSC. The following options will be acceptable approaches for providing the required COFS II flight system:

(1) Baseline Configuration - The contractor will refurbish and modify the government furnished hoop-column antenna and attach it to the COFS I beam by means of a two-degree-of-freedom gimbal to provide the required technology development capability.

(2) Contractor Hardware - The contractor or a team of contractors may propose an alternate flight system utilizing contractor provided hardware which will satisfy the technical requirements of the COFS II project and provide at a minimum, equivalent technology development capability as the COFS II baseline configuration.

(3) Combined Contractor, Government Furnished Equipment - The contractor or team of contractors may propose an alternate flight system utilizing a combination of contractor provided flight hardware and government furnished equipment such as the hoop-column antenna or COFS I Mast. The resultant flight system must satisfy the technical requirements of the COFS II project and provide at the minimum, equivalent technology development capability as the COFS II baseline configuration.

The cost of options (2) or (3) must remain within the available contractual funding and funding profile or be cost shared by the contractor(s).

● RFP WILL INCLUDE:

- BASELINE REQUIREMENTS
- FUNDING LIMITATION

● RFP WILL PERMIT BROAD INDUSTRY PARTICIPATION:

- HOOP-COLUMN
- ALTERNATIVE ANTENNA
- OTHER COMPONENTS

CONCLUDING REMARKS

The COFS II project is a complex and ambitious undertaking which will address several critical technology areas. Among them are modeling, structural dynamics, controls, and ground testing issues which are not only germane to this effort, but to other large space structure programs being contemplated. This effort requires the early integration of controls and structural dynamics considerations in order to achieve mission success. Several technology advances must be achieved in the areas of system modelling, control synthesis and methodology, sensor/actuator development, and ground testing techniques for system evaluation and on-orbit performance prediction and verification. This project offers a unique opportunity for the integration of several disciplines to produce technology advances which will benefit many future programs. In addition, the opportunities available to participate in the various levels in the phases of this project, e.g., analytical development and modelling, ground testing, and flight testing, permit for the involvement of a significant number of interested researchers and organizations from government, universities and industry.

- **OPPORTUNITIES FOR RESEARCH IN MANY DISCIPLINES**
- **SYNERGISTIC COMBINATION OF ANALYTICAL, GROUND & FLIGHT EXPERIMENT DEVELOPMENTS**
- **UNIQUE OPPORTUNITY FOR GUEST INVESTIGATOR PARTICIPATION AT ALL LEVELS**